Influence of the hurricane on the structure of the thermocline

Parts I and III

by

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INFLUENCE OF THE HURRICANE ON THE STRUCTURE OF THE THERMOCLINE 1/ 2/
PART I

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Hurricane Carla entered the Gulf of Mexico through the Yucatán Straits on September 7, 1961. From there it traveled northwesterly and grew to be one of the five severest hurricanes to invade the Gulf since 1837. By September 10, as it approached the Texas coast (Figure I-1), pressures in the center were 931.2 mb, and winds of 130 knots whirled around the eye. Because of the early and continuous advisories issued by the U. S. Weather Bureau, nearly 500,000 people evacuated the coastal regions. Thus, despite the fury of the storm and the accompanying storm surges (a maximum of 7 meters where the storm crossed the coast), few persons were injured.

The energy exchange between the sea and the atmosphere is several orders of magnitude greater during a hurricane than in less severe tropical cyclones. Hurricanes provide, therefore, a unique 'laboratory' for investigations of air-sea interaction. The taking of *in situ* measurements of water temperature changes during hurricanes is, however, almost impossible. No work can be done aboard ship. Weather buoys have broken from their moorings, never again to be seen, and towers have foundered. Thus, changes in the water temperature distribution affected by Hurricane Carla were investigated by necessity, after the passage of the storm, when the waters were peaceful again.

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1 Contribution No. 239, Bureau of Commercial Fisheries Biological Laboratory, Galveston, Texas.
2 This article is a modification of a paper by Stevenson & Armstrong (1965).

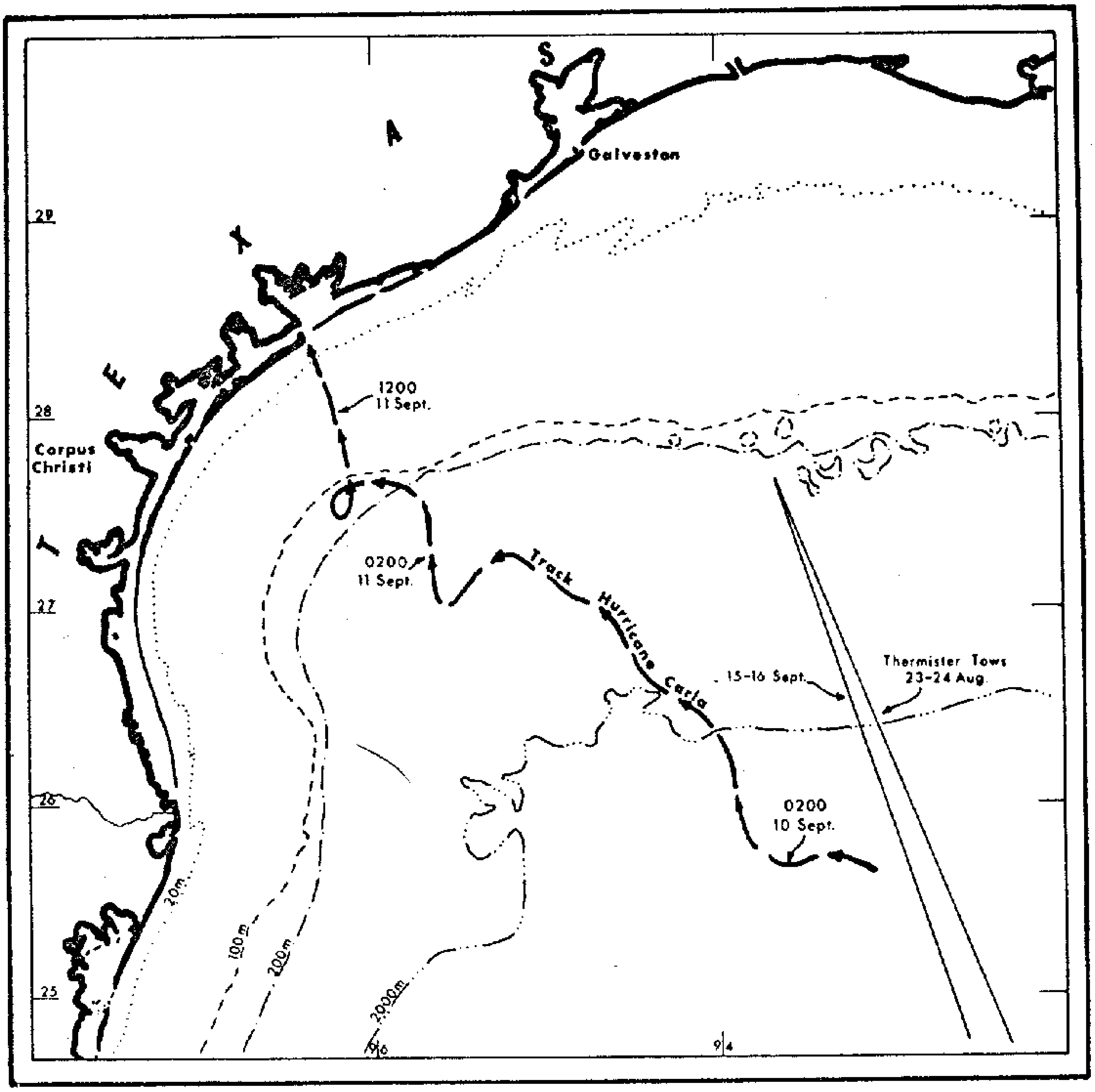

Figure I-1.--The track of Hurricane Carla on September 10 and 11, 1961, as plotted by U. S. Weather Bureau Radar at Corpus Christi and Galveston, Texas, and locations of thermistor-chain tows made from the R/V HIDALGO.

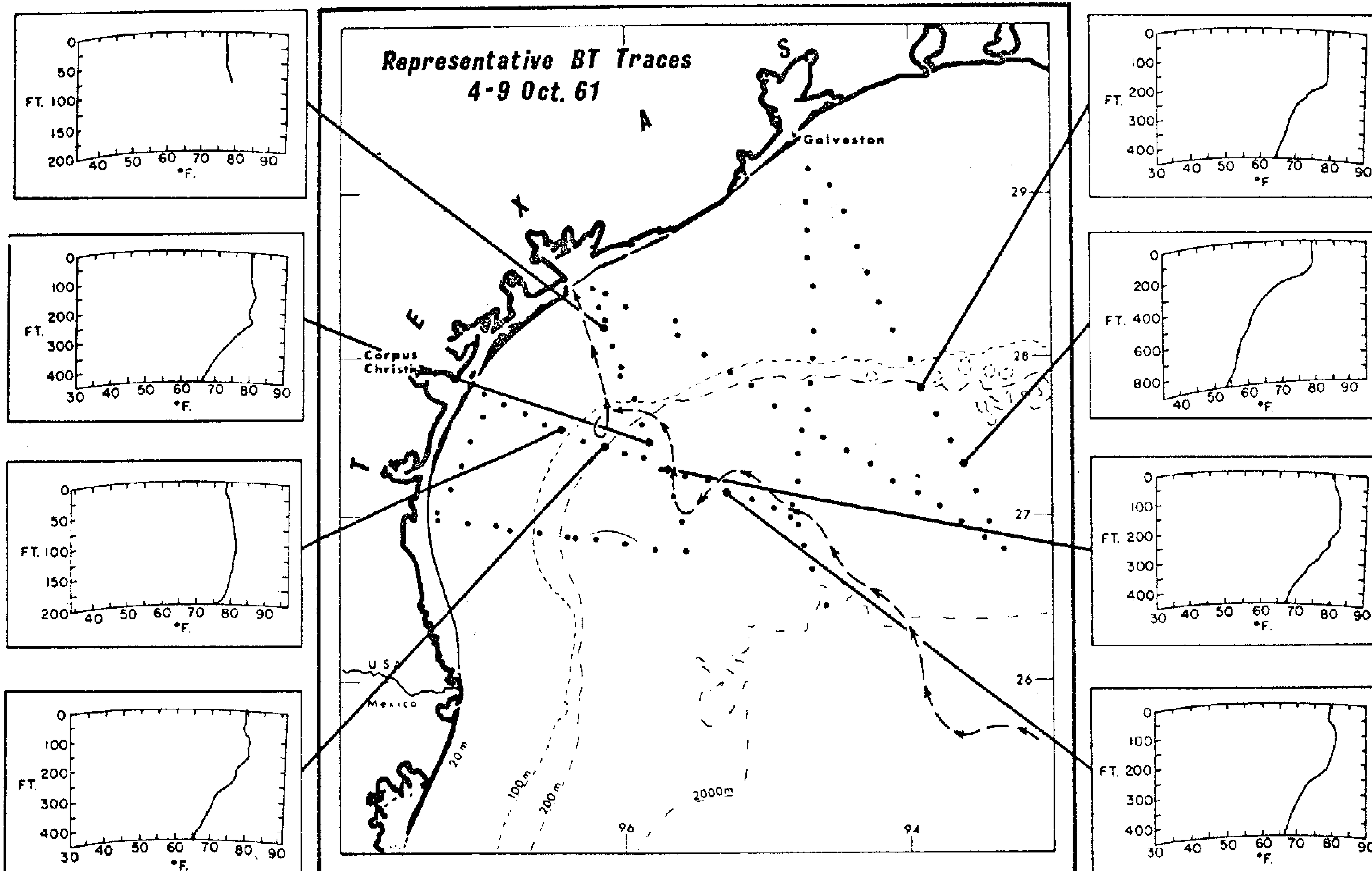

Figure I-2.--Location of bathythermograph casts made from the R/V HIDALGO on October 4-9, 1961, and representative temperature traces.

Northwest Gulf Waters in the Fall of 1961

Throughout the year a layer of low-salinity water lies along the coast of the northwest Gulf. Variations in the salinity, width, and thickness of the layer depend primarily on the volume of river runoff coming through the numerous estuaries and lagoons (Harrington, 1966). Usually the surface salinity is approximately 30.00% close to shore, and this salinity may extend to depths of 20 to 30 meters; at 40 to 50 meters the salinity increases to 36.00%. A salinity of 36.50% is normal at distances of 30 to 50 km from the coast.

Rainfall along the Texas Coast was considerably greater than mean conditions during the summer of 1961 (Weather-Bureau-Galveston). It is clear then that the brackish surface water extended farther from shore than usual -- probably about 120 km from the coast between the Mexican border and Galveston, Texas. It was over this wide brackish layer that Hurricane Carla swept on September 10 and 11 (Figure I-1).

The R/V HIDALGO, Texas A&M University, cruised in the northwest Gulf, October 4-9. Scientists aboard were investigating the distribution of temperature and salinity. Many bathythermograms revealed temperature inversions as great as 2.5°C, extending to depths of 83 meters (Figure I-2). The inversions were all within the area of the brackish bulge (Figure I-3). Salinities near shore were as low as 29.76% at the surface and were 30.00 to 31.00% to depths of 40 meters. In most of this area, water of 36.00% lay below 100 meters, although at 70 to 80 meters the salinities were usually near 35.00% (Figure I-4a and 4b). Waters with the steepest salinity gradient were within 110 km of the shore, and surface waters having salinities of 33.00%, or less, extended to 210 km from shore (Figure I-4a). The typically steep salinity gradients are noted in Figure I-4b.

Apparently the loss of heat in the surface waters to the hurricane atmosphere lowered the water temperature, forming the inversions, and, because of the brackish layer, the lowered temperatures did not result in a density instability in the water. From climatologic records and previous data collected during research cruises over the outer shelf of the northwest Gulf, it is known that normal changes in water temperatures in September and October are negligible. This relation has been substantiated by applying the techniques presented by Laevastu (1960) to the factors that influence heating and cooling of surface waters. Furthermore, the 91 bathythermograms taken on the October 4-9 cruise showed no indication of heating, or further cooling, of the surface waters in the month after Hurricane Carla.

In the weeks after Hurricane Carla, winds over the northwest Gulf blew at low velocities, and several successive days

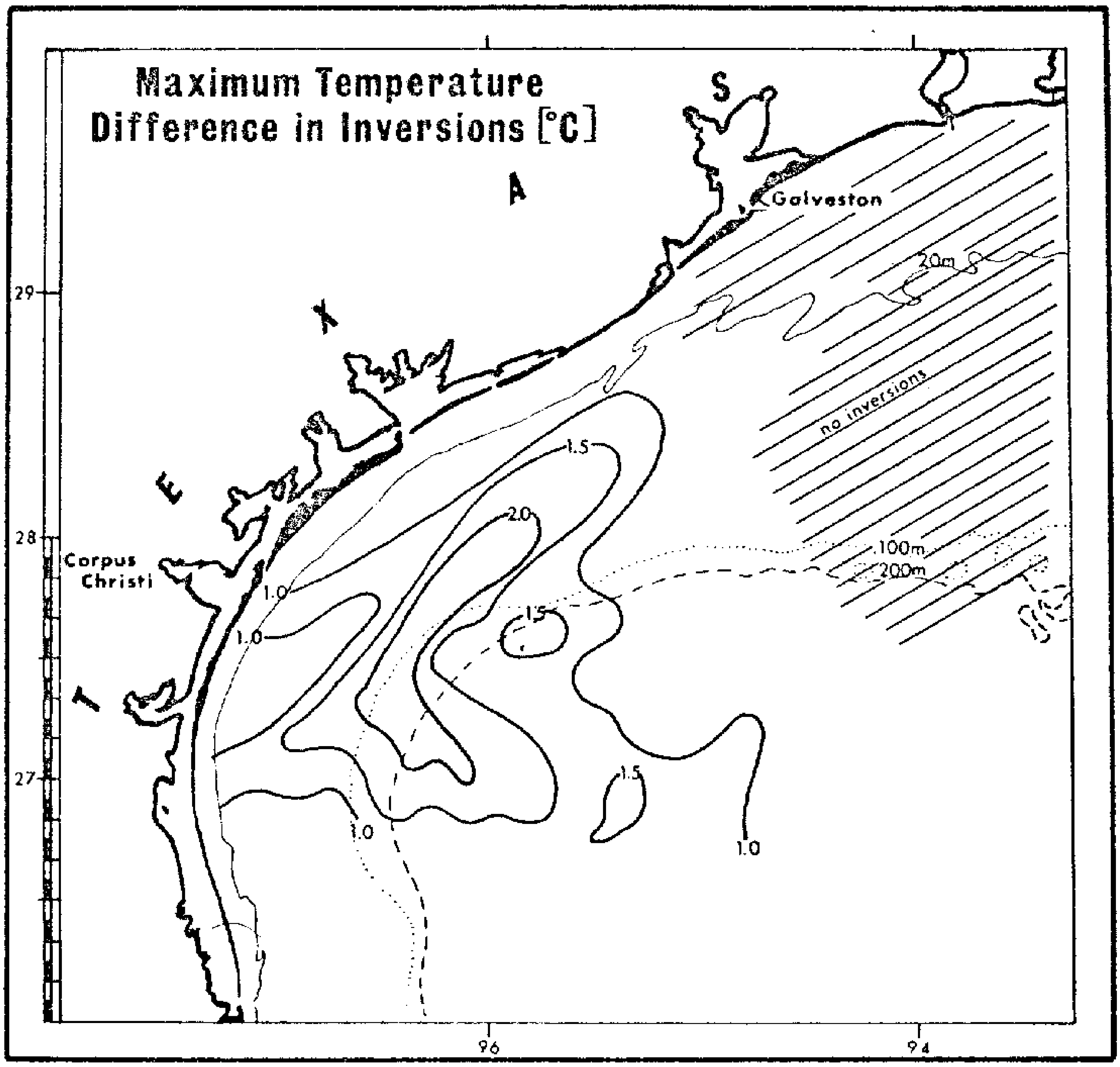

Figure I-3.--The distribution of maximum temperature differences in inversions as deduced from data gathered on October 4-9, 1961.

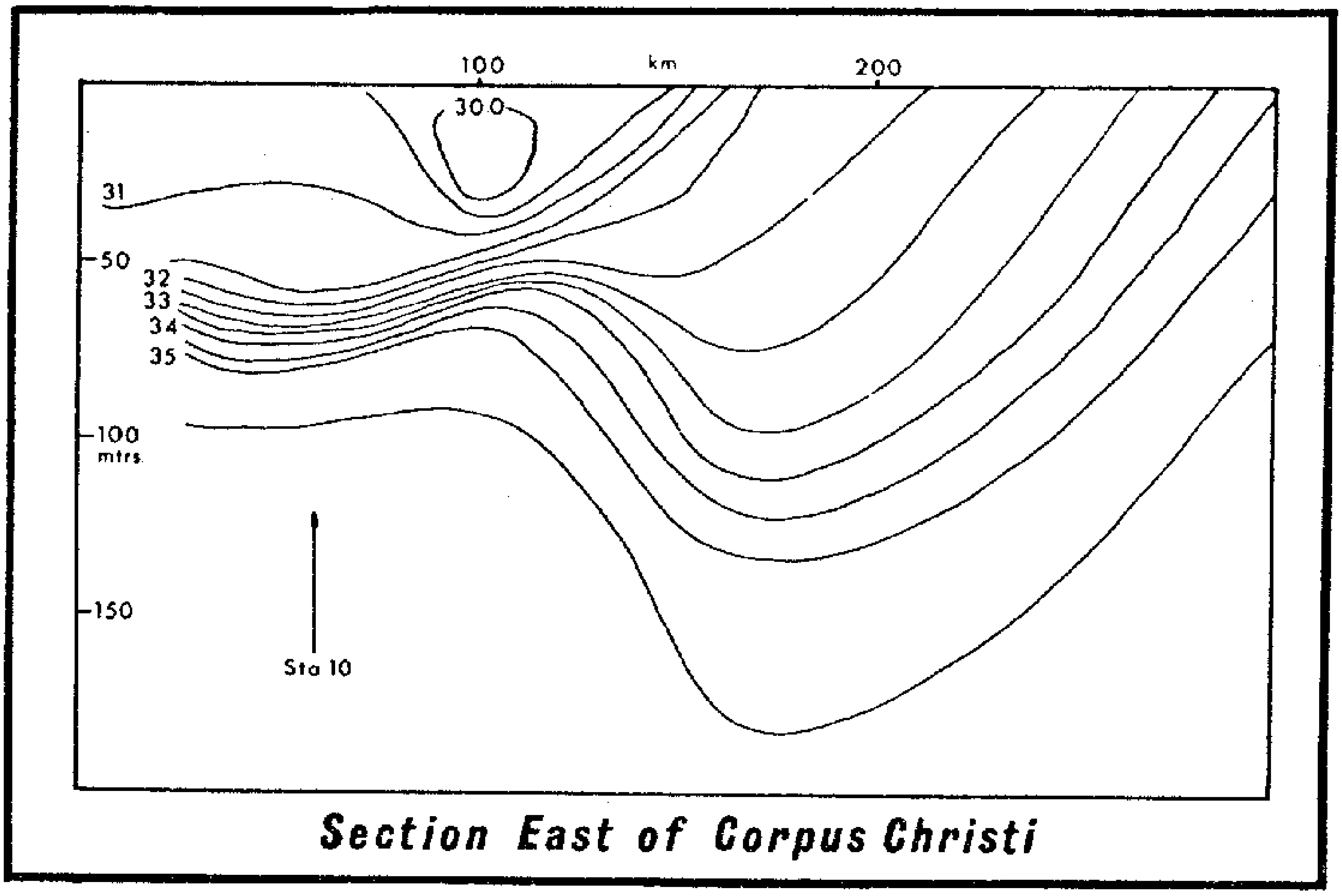

Figure I-4a.--Salinity Profile extending east of Corpus Christi, Texas. The samples were collected on October 7 and 8, 1961.

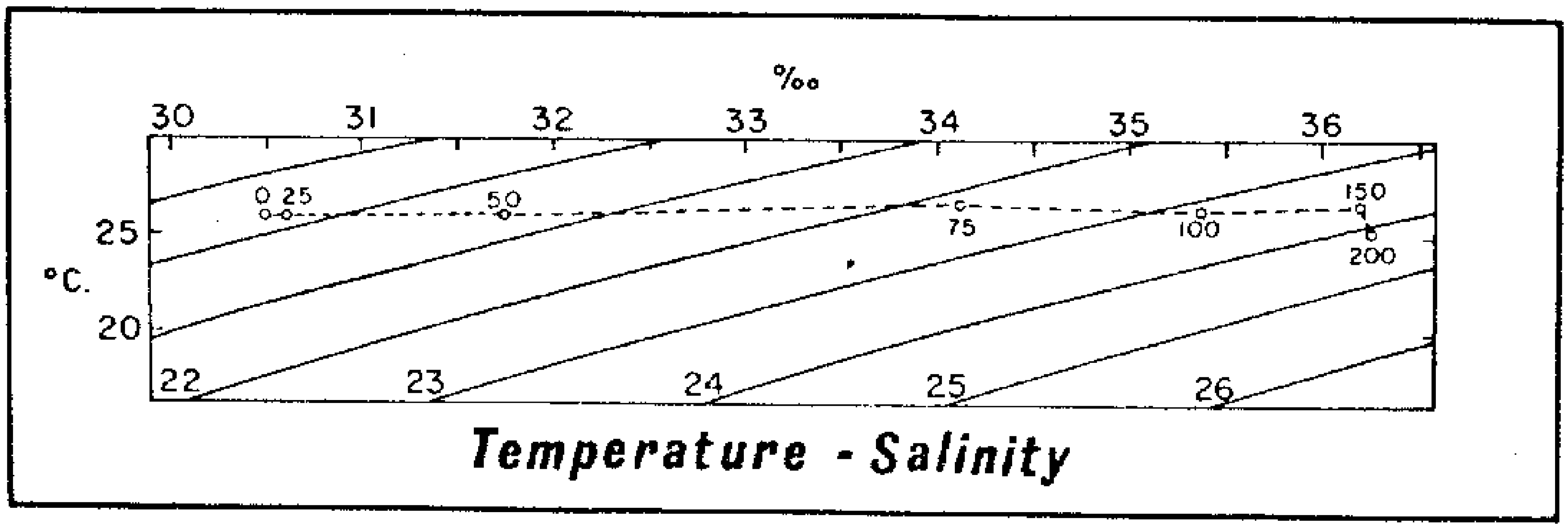

Figure I-4b.--Temperature-Salinity diagram at HIDALGO Station 10 (see Figure 4a) on October 7, 1961.

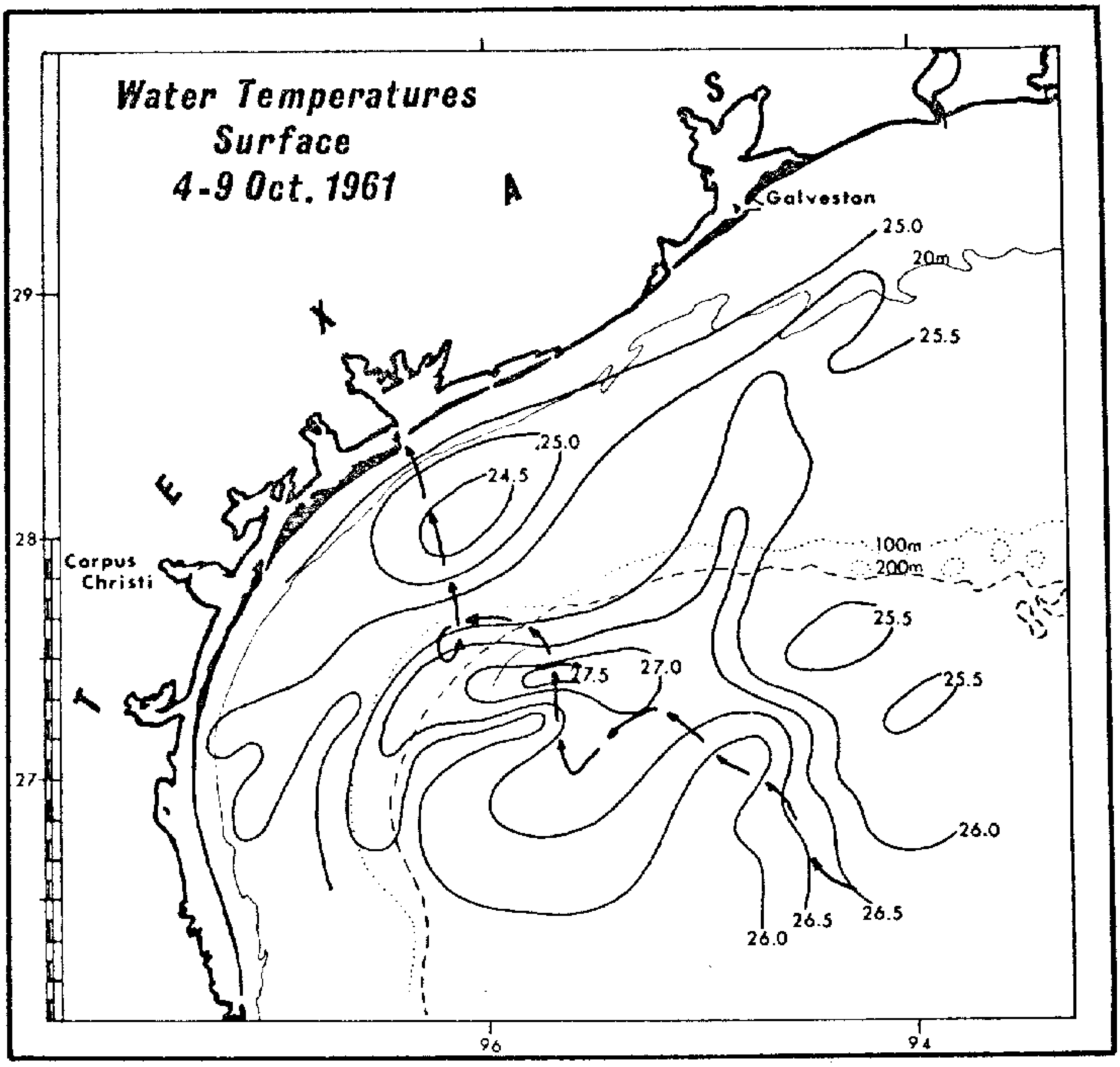

Figure I-5. --The distribution of surface water temperatures on October 4-9, 1961.

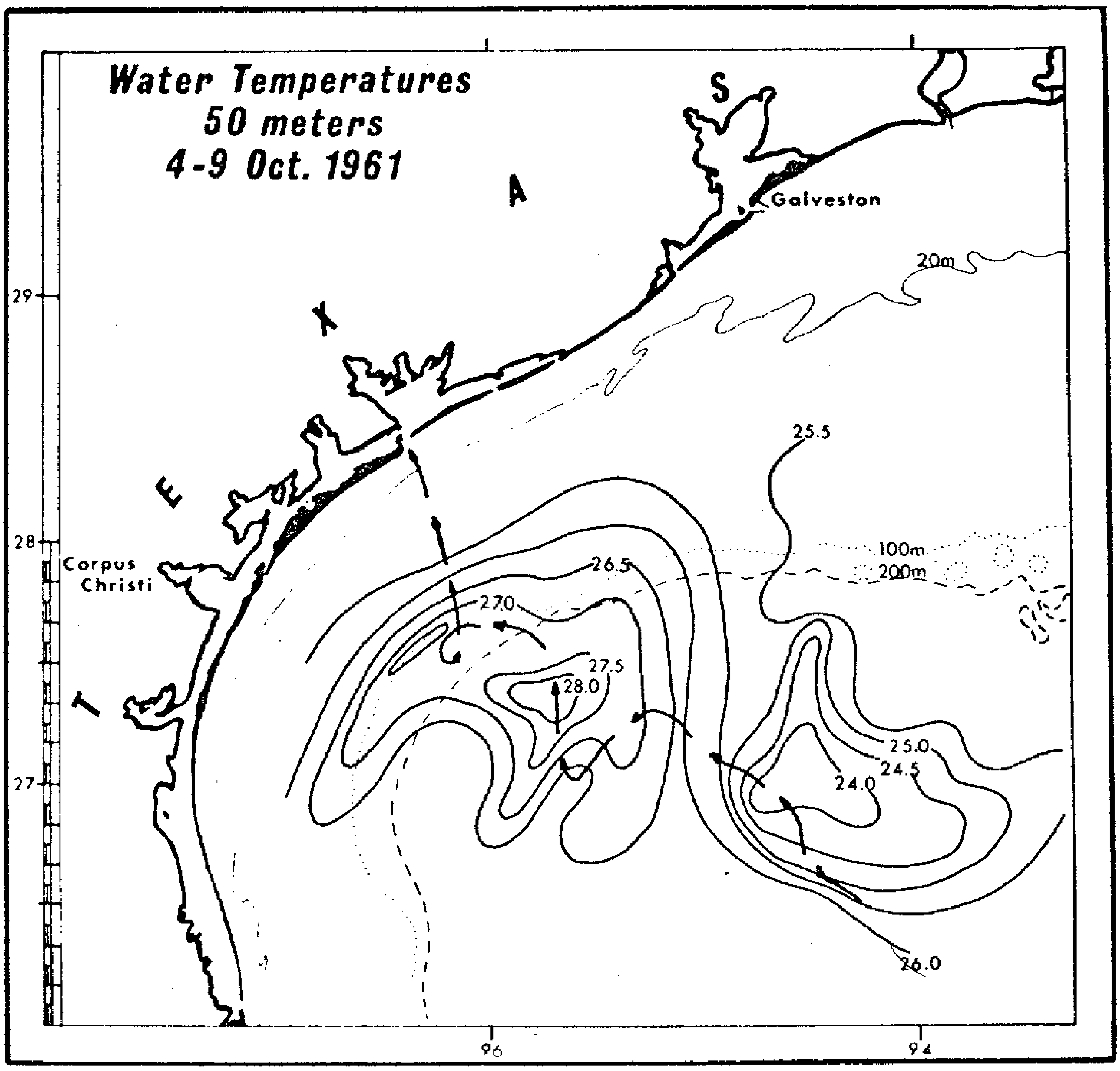

Figure I-6.--The distribution of water temperatures at a depth of 50 meters on October 4-9, 1961.

had light and variable air. The wind was, as normal, from the southeast but was not strong enough to produce wind-drift currents that would re-establish normal temperature distribution. Isosteric surfaces, computed from data gathered on October 4-9, were essentially flat. Therefore, no significant density currents were present.

On the basis of these considerations it was concluded that the water-temperature structure of the northwest Gulf retained, for at least the succeeding 4 weeks, the dominant characteristics formed during Hurricane Carla. The inversions which were measured during October 4-9 were believed little modified from the configuration immediately after the hurricane.

To the southeast of Galveston, where the vertical distribution of salinity was nearly isohaline, the heat loss from the surface caused instability in the upper layers. The consequent convective stirring produced an isothermal layer which extended to depths of 60 meters (Figure I-2).

Temperature Distribution

The distribution of surface water temperatures in early October reflected the influence of Carla (Figure I-5). Warmer water was centered in the area where the hurricane deviated from its northwesterly course, whereas colder water was on both sides of the hurricane track and over that part of the shallow shelf which was beneath the track of the storm.

At depths of 50 meters (Figure I-6), the main 'cells' of warm and cold water were even more sharply defined. The effects of the temperature inversions were noted where temperatures were slightly greater than 28.0°C, which was just more than 0.5°C warmer than those at the immediately overlying surface. Farther from shore and to the right of the hurricane track, the cooler water indicated modified temperature structures where typical Gulf-water salinities occurred.

The influence of the hurricane was not restricted to the surface layers, for there was an upward transport of heat from depths greater than 100 meters. This movement was best exemplified by changes which took place in the vertical and horizontal configuration of the thermocline. For Figures I-7 and 8, semi-diagrammatic sketches were drawn from data gathered by thermistor-chain tows along the tracks indicated in Figure I-1. (Figures I-7 and 8 were drawn from average values of the data obtained by the thermistor-chain. The temperatures and the depths of the isotherms differ to some extent, therefore, from those plotted directly from the bathythermograms.) On August 23 the thermocline was typical of these Gulf waters, exhibiting a flat

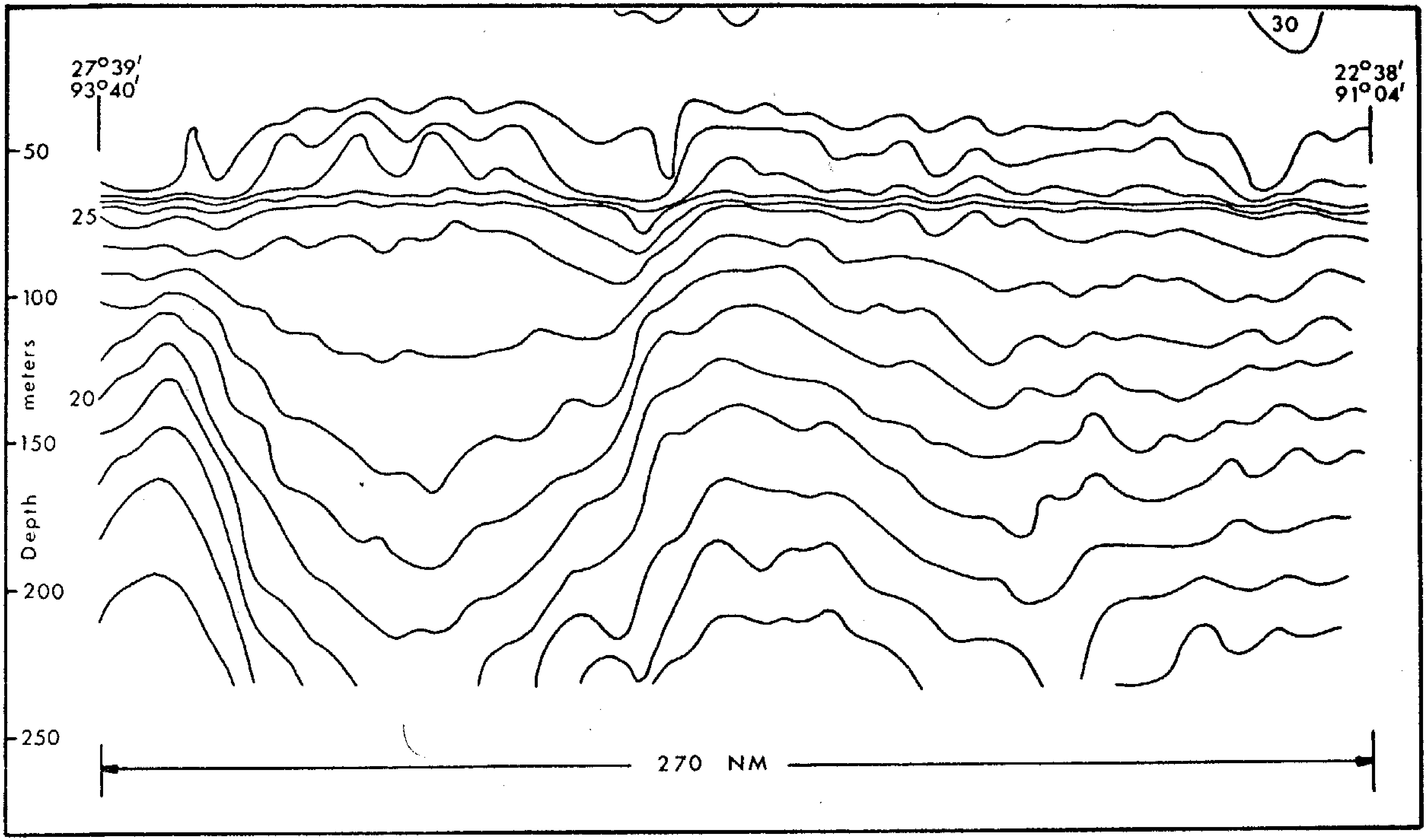

Figure I-7. --A semidiagrammatic representation of the vertical water temperature distribution south of Galveston on August 23, 1961. Data were obtained from a thermistor-chain tow made from the R/V HIDALGO.

Temperature Profile

September 15, 1961

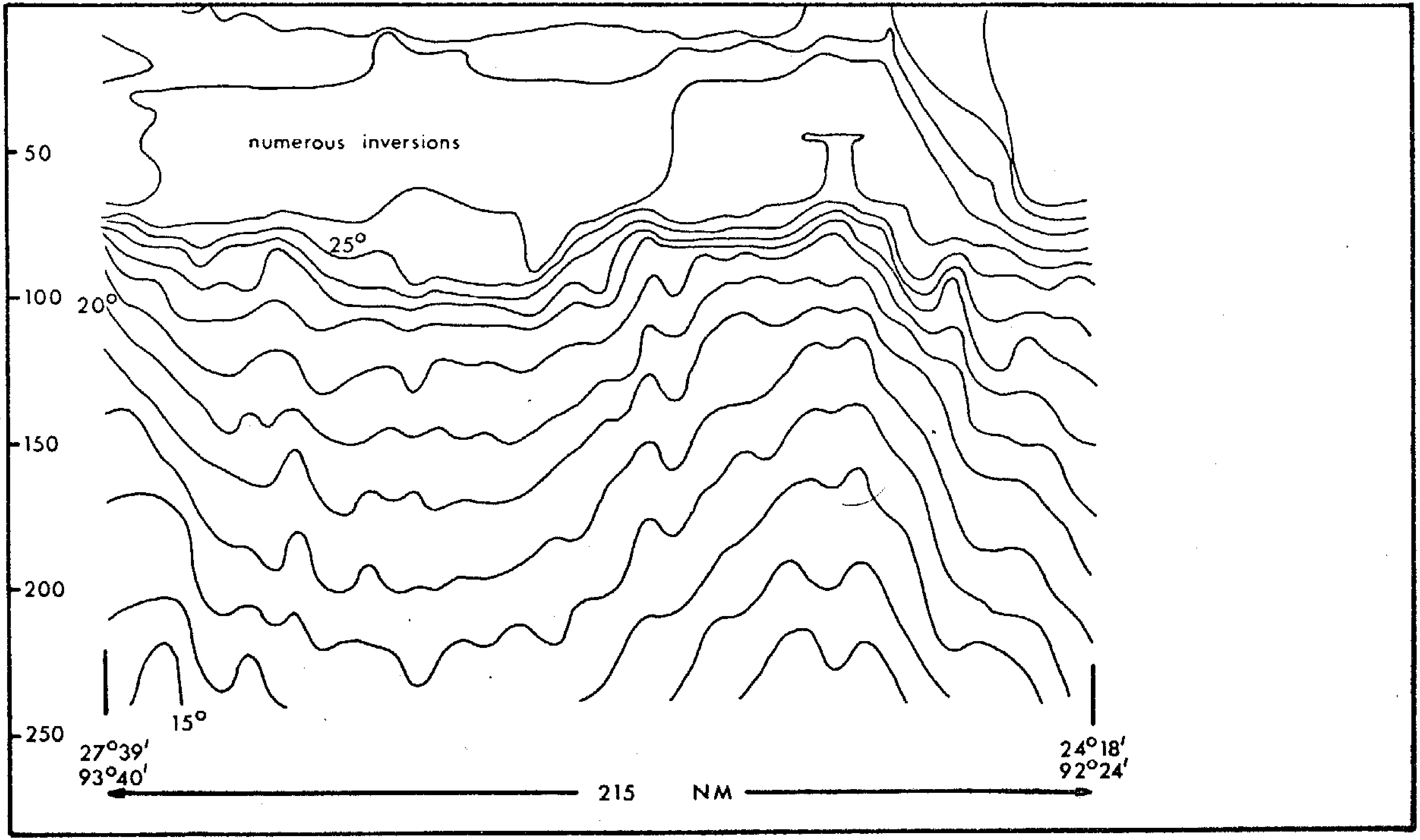

Figure I-8.--A semidiagrammatic representation of the vertical water temperature distribution south of Galveston on September 15, 1961. Data were obtained from a thermistor-chain tow made from the R/V HIDALGO.

surface at depths of 65 to 70 meters. The thickness of the thermocline decreased in an offshore direction, but the 26°C isotherm remained as the upper limit throughout the area measured.

During the hurricane, 26°C water was carried into the disturbed surface layer, and the 25°C isotherm marked the upper part of the thermocline on September 15 (Figure I-8). The surface of the thermocline was no longer flat, but had been depressed shoreward and seaward of the region where the tracks of the hurricane and thermistor tow crossed. A comparison of the two profiles (Figures I-7 and 8) reveals that after the storm the 24° and 25°C isotherms were deeper in the nearshore area and that those below the thermocline were 18 to 70 meters shallower than on August 25. The greater upward displacement was in the deeper water (note the 20°C isotherm, for example).

The topography of the 25°C isotherm (top of the thermocline) during October 4-9 closely resembled the configuration of the temperature distribution. Whereas the thermoclinal surface was generally between 50 and 70 meters south of Galveston and seaward of the shelf break, it was depressed to depths of 102 meters to the west (Figure I-8). The thermocline decreased abruptly in depth from the edge of the shelf shoreward, and, along the track of the hurricane, was absent in waters shoaler than 50 meters (see Figure I-2).

Summary

The cruises of the R/V HIDALGO in 1961 were certainly "cruises of opportunity," for the extent and magnitude of changes in the waters after a hurricane passage were unknown. Nevertheless, the temperature profile obtained on September 15, 1961 (Figure I-8), is quite similar to those from data gathered in 1964. The "stovepipe" effect beneath the "eye position" is easily noted, as is the depression of the thermocline on either side. It would appear that Leipper's analysis (1966) is correct -- that the warmer surface water was transported from the areas of the eye to lie in a "trough" along the borders of the "eye track," and that the removal of the surface water beneath the eye developed a divergence which produced the upwelling of deeper and cooler water.

The isotherms below the thermocline were at lesser depths after Hurricane Carla than before (compare Figures I-7 and 8), at least to the depths measured (about 230 meters). The configuration, however, of the isotherms below 100 meters (perhaps even 75 meters) on September 15, was nearly identical to that existing before the hurricane. This close similarity existed because Hurricane Carla crossed the southern border of a western-Gulf eddy, which formed the configuration of the isotherms below the thermocline before the hurricane. Clearly this isotherm configuration was not altered as the result of any reaction to the storm, but the isotherm depth did change.

One initial problem was to determine the origin of the deep temperature inversions. It is unlikely that the temperature inversions which were measured can have resulted from any mechanism other than cooling. Upwelling does not produce such vertical temperature distributions. An introduction of cool, low-salinity water, on the other hand, could produce inversions similar to those observed. The source of low-salinity water, however, is the estuarine system of the Texas coast which, during late summer, contains warm water (temperatures of 28^{o}-$32^{o}C$). Furthermore, and as discussed by Leipper (see part II), the wind field around hurricanes develops a wind drift (storm surges) and the water is driven into, rather than out of, the lagoons and estuaries.

Considering, then, that the inversions represent a certain amount of heat loss from the water, the magnitude and depth of the inversions would be controlled by (1) the thickness and salinity of the surface layer, (2) the intensity of the storm and the consequent reaction of the water, or (3) both.

If the water temperature is decreased sufficiently in any water to produce instability, convective stirring must take place (in addition to mechanical stirring by wave action). This stirring would eliminate inversions and a thoroughly mixed layer would be formed (as in the waters southeast of Galveston). If cooling were insufficient to cause convective stirring in the brackish surface water, but extended below the low-salinity layer, a mixed zone below the inversions would be expected. None was noted (see Figure I-2).

The salinity of the surface waters would control the magnitude of the temperature inversions. If cooling were to bring the water to a density instability, convective mixing would result. Conceivably, then, the loss of heat could have produced greater temperature differences than observed in the inversions.

The temperature-salinity curve in Figure I-4b shows that the water to 150 meters (at this station) was far less stable than normally encountered, but still did not reach a neutral stability (a frequent condition in the Gulf during the winter). The temperature decrease was not, therefore, the maximum possible without overturning under the prevailing water conditions. Thus, the observed temperature differences in the inversions are considered minimum.

Upwelling and Cooling

The discussion by Leipper (see Part II) of the water temperatures after Hurricane Hilda impressively described the mass transport of surface water from the region underlying the eye. Such a picture is not obvious from the data obtained after Hurricane Carla. Rather, the temperature inversions are ascribed to cooling of the water.

Certainly, if there were upwelling in addition to the heat loss indicated by the inversions measured in 1961, it is clear that the cooling extended to an even greater depth than indicated by the temperature curves. With the data we have, any estimation of how much greater would be pure folly. Nonetheless, it now seems apparent that the heat loss from the water must have been orders of magnitude more than the 2.2×10^{18} cal/24 hours originally calculated (Stevenson & Armstrong, 1965).

Acknowledgements

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PART III [1]

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I think you can begin to understand that our investigations of hurricanes have been somewhat fortuitous. It almost seems that we spend the summer hoping that if one does come, a ship will be available.

Dale Leipper has mentioned some of the deep-water temperature structures before and after Hurricane Betsy. Of interest to fishery oceanographers is the effect of hurricanes in the shallow water -- particularly in the Gulf where the great shrimp fishery is located. I shall discuss now the modification of the water temperatures over the Gulf shelf by Hurricane Betsy.

Hurricane Betsy entered the Gulf of Mexico on September 8, 1965, after crossing the southern tip of Florida. The storm followed a northwesterly path and penetrated the coast west of New Orleans, Louisiana, in the late hours of September 9. Hurricane-velocity winds extended 130 kilometers from the center and wind speeds of 190 km/hr were measured near the eye. The average forward speed of the storm as it crossed the Gulf of Mexico was 24 km/hr.

The complete track of Hurricane Betsy, from the time it was first noted as a tropical depression off the northeast coast of South America, through its period as a tropical storm northeast of Haiti, and its life as a hurricane are shown in Figure III-1. During early life, as a tropical depression, Betsy was photographed by Col. Gordon Cooper and Cdr. Charles Conrad as they orbited on GT-5 (Figure III-2) near the mouth of the Orinoco River, Guyana (British Guiana). The astronauts did not know that this was a tropical depression; that this was Hurricane Betsy at its birth, for they could have centered it in the photograph.

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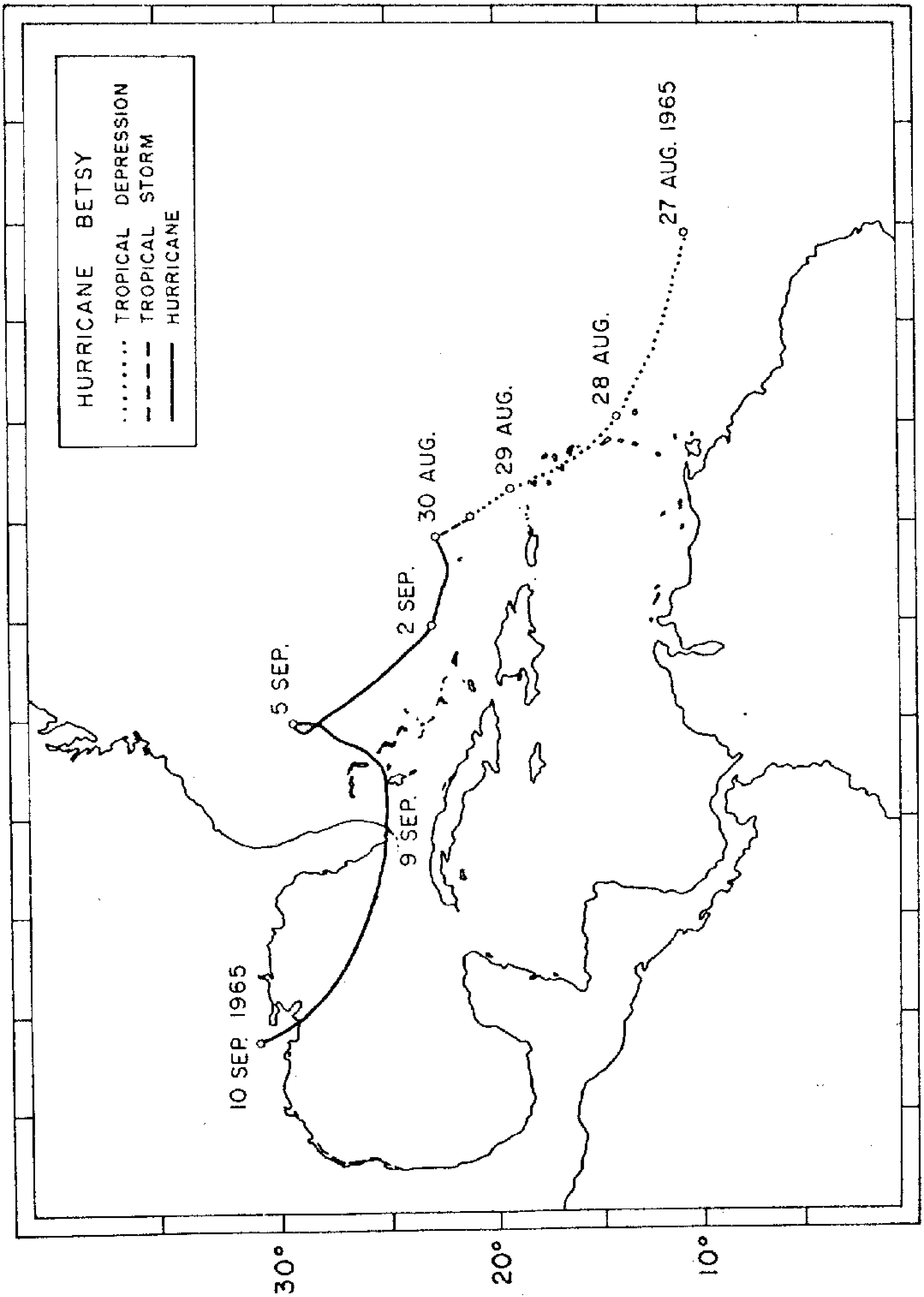

Figure III-1. --Track of Hurricane Betsy, including those areas over which the storm traveled during its period of a tropical depression and a tropical storm.

Figure III-2.--Photograph of the area off the coast of British Guiana showing embryonic Hurricane Betsy in foreground. Photograph was taken on Gemini V by pilots Lt. Col. L.G. Cooper and Cdr. Charles Conrad, Jr.

SCAN FROM POOR XEROX

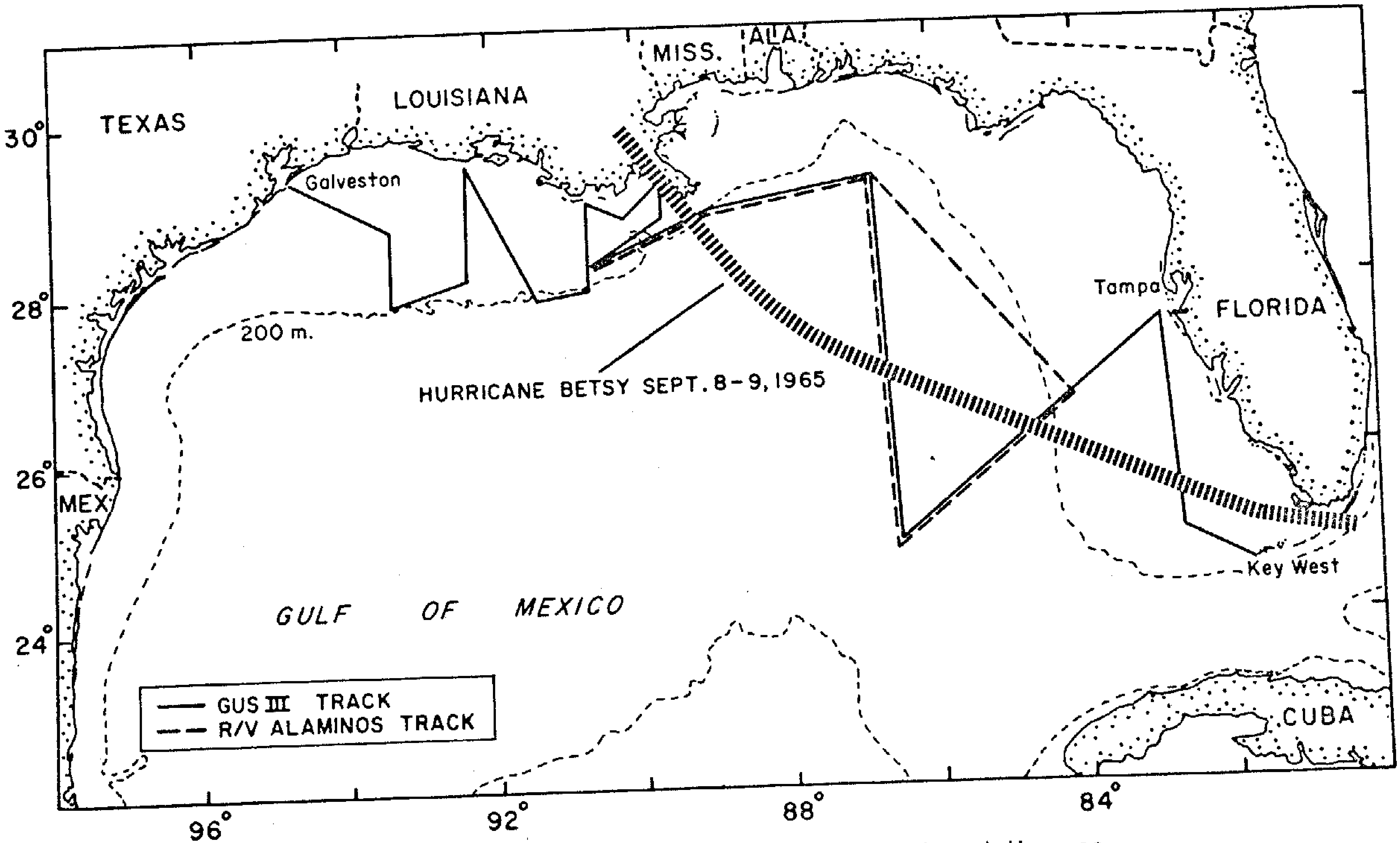

Figure III-3.--Part of the tracks of oceanographic stations occupied by the R/V ALAMINOS and complete track of the M/V GUS III in August and September, 1965.

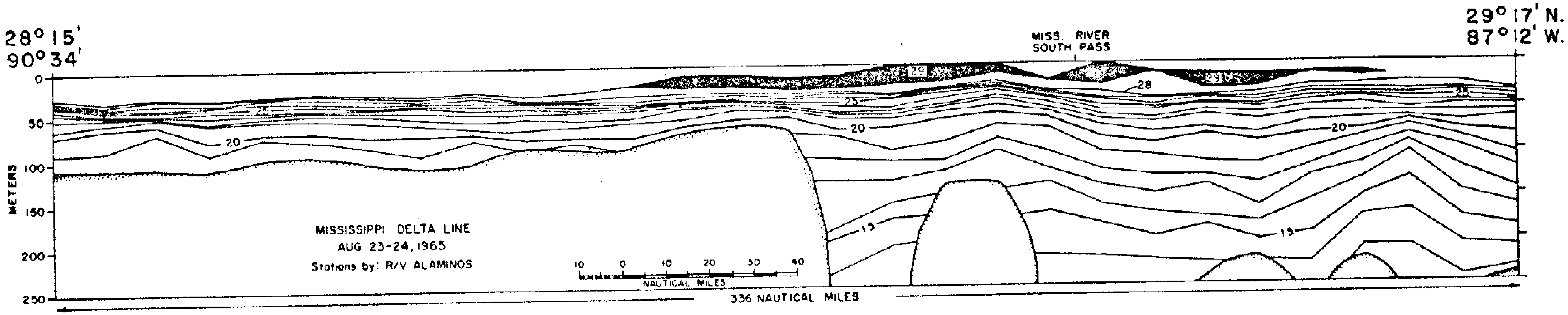

Figure III-4a.--Temperature profile in the waters off the Mississippi Delta, from data gathered aboard the R/V ALAMINOS, August 23-24, 1965. Warm Mississippi River water, with temperature inversions of 1-2.5°C, is shown in black.

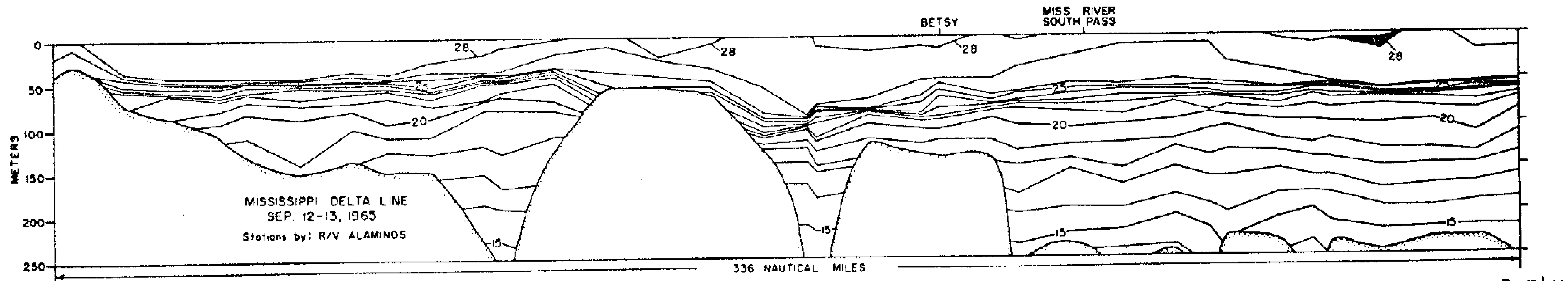

Figure III-4b.--Temperature profile in the waters off the Mississippi Delta, from data gathered aboard the R/V ALAMINOS, September 12-13, 1965. Note: The only occurrence of water with temperature inversions is to the east of the Delta.

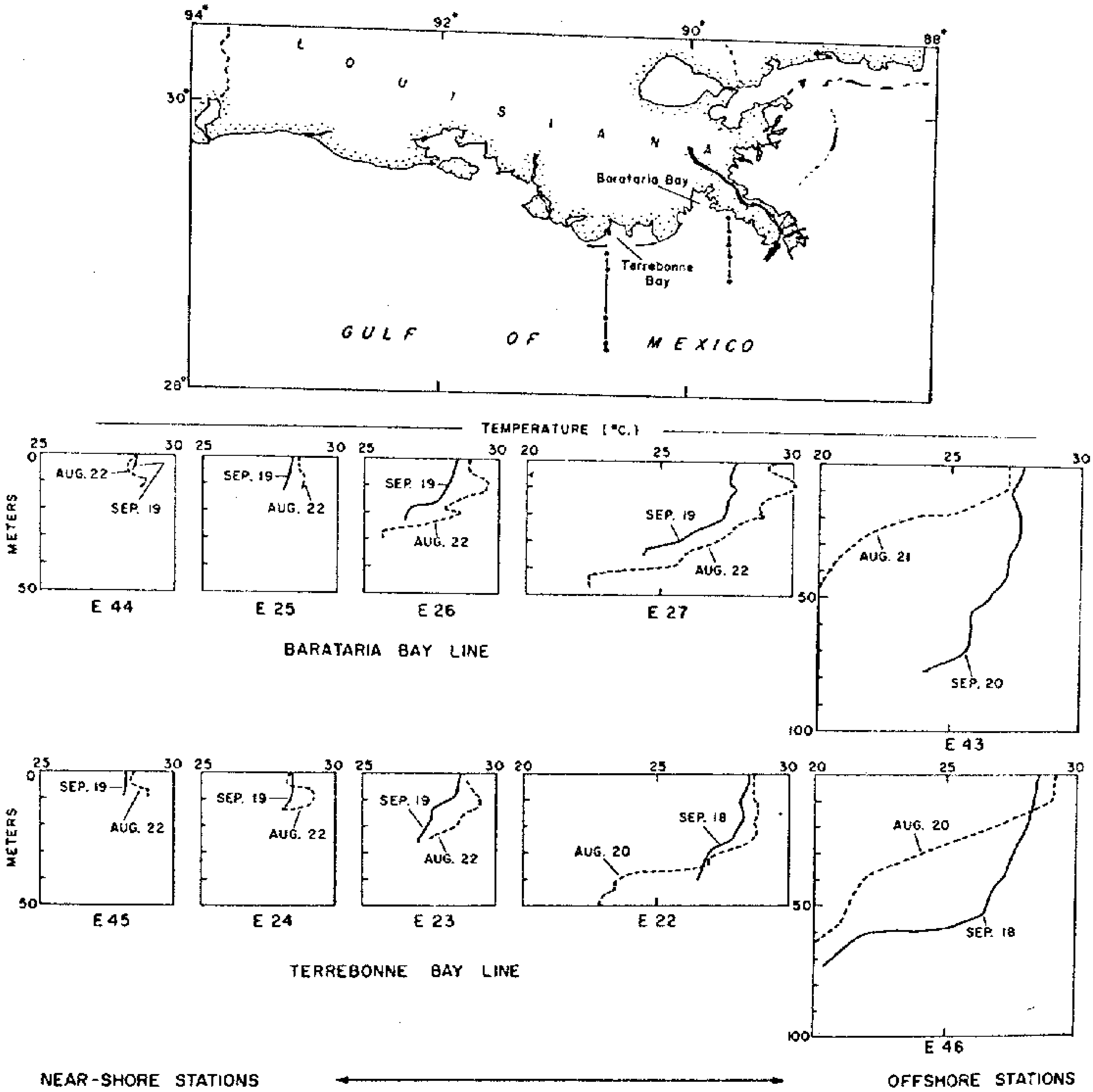

Figure III-5. --Reconstruction of temperature traces from bathythermograph casts made from the M/V GUS III in August and September, 1965.

The R/V ALAMINOS, Texas A&M University, with Dr. Leipper as chief scientist, cruised along the edge of the continental shelf and occupied a series of oceanographic stations on August 23-24, 1965. Immediately after the storm, on September 12-13, the ALAMINOS cruised again along the same track. Ten days later, September 20-22, the M/V GUS III, Bureau of Commercial Fisheries, occupied stations along one of the tracks made earlier by the ALAMINOS (Figure III-3). The data collected on these cruises allowed, for the first time, analyses of the water structure immediately before and after the hurricane.

In August, the water near the Mississippi Delta had a warm surface layer spread over water of normal temperature (Figure III-4a). The top of the thermocline was bounded by the 28°C and 29°C isotherms and began at depths of 20 to 30 meters. The thermocline was nearly horizontal, in an east-west direction, and the net water motion was parallel to the coast. (The GUS III encountered westerly flowing currents of 3-5 knots on September 20-21.) Hurricane Betsy crossed these waters about 25 nautical miles west of South Pass.

The temperature structure shortly after the passing of Hurricane Betsy was considerably different from that which prevailed in August (Figure III-4b). The thermocline was deeper in all areas than it was in August -- the depth of the top varied from 40 to 90 meters. The greatest depths of the thermocline were in the water which lay under the eye of the storm.

As Dr. Leipper has mentioned, the Ekman transport of water is away from the eye of a hurricane. Water is pushed ahead of the hurricane, therefore. As it reaches the coast, a storm surge occurs and, at the same time, the warm surface water forms a deepening wedge along the coast (Leipper, 1966). This effect can be noted in the Mississippi Delta profile (Figure III-4b) where water of 25°C lies atop the shelf after the hurricane, whereas 19°C water covered the shelf in August (Figure III-4a). The dramatic change in the temperature structure off Barataria and Terrebonne Bays before and after the hurricane (Figure III-5) attests to the hurricane influence. Note especially Station E-43 off Barataria Bay (over which the hurricane passed) and E-46 off Terrebonne Bay. The change in the structure of the thermocline off Terrebonne and Barataria Bays indicates that the intrusion of offshore water was extensive and produced significant changes in the temperature structure.

The isotherm marking the top of the thermocline after the hurricane differed from the August condition; it was cooler by 2°-3°C along much of the section, and differed from one place to another along a transect across the path of the hurricane (Figure III-4a and 4b; top of the thermocline was 28° -29°C in Au-

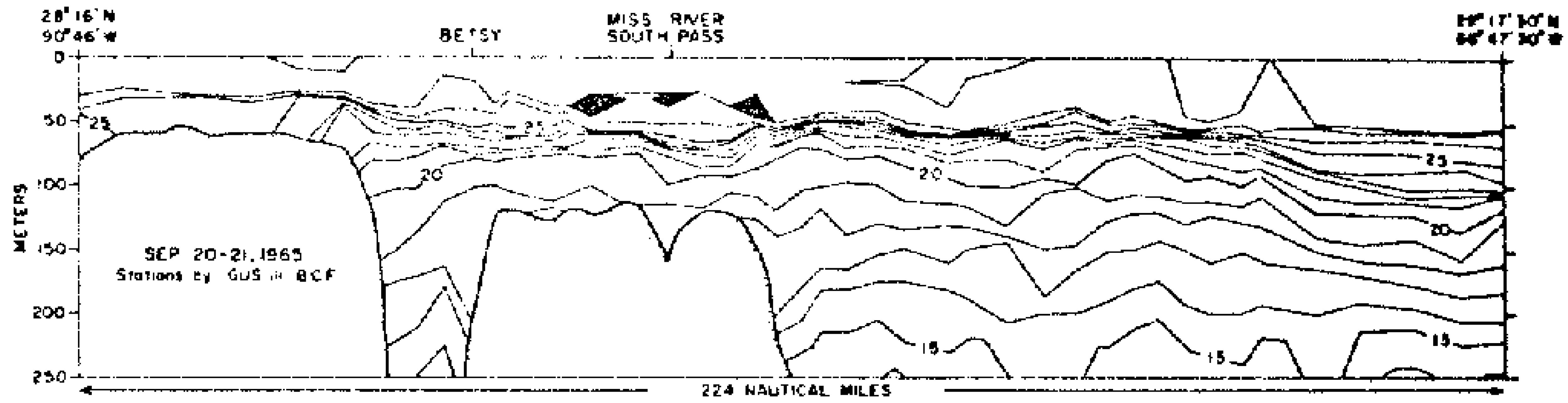

Figure III-6a.--Temperature profile in the waters off the Mississippi Delta, from datagathered aboard the M/V GUS III, September 20-21, 1965. (Blacked-in portions indicate temperature inversions.)

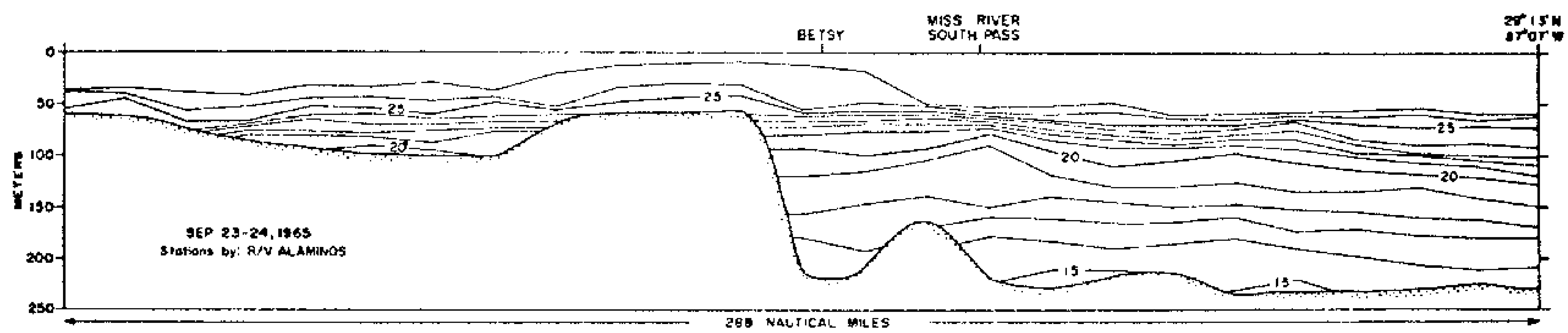

Figure III-6b.--Temperature profile in the waters off the Mississippi Delta, from datagathered aboard the M/V GUS III, September 23-24, 1965.

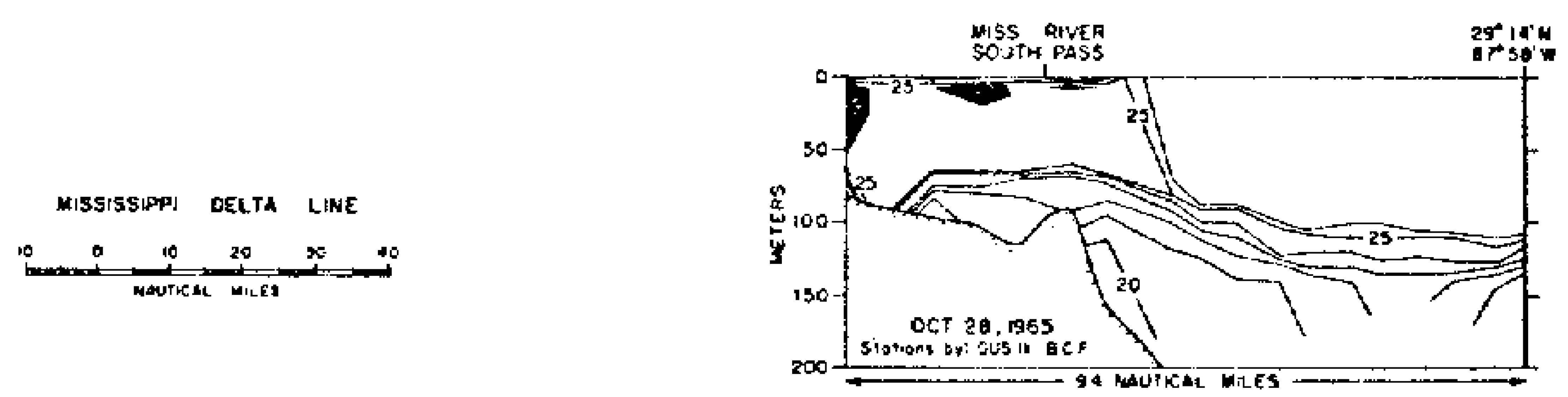

Figure III-6c.--Temperature profile in the waters off the Mississippi Delta, from data gathered aboard the M/V GUS III, October 28, 1965. (Blacked-in portions indicate temperature inversions.)

gust and 26° -28°C in September). Beneath and for about 100 nautical miles east and west of the path of the eye, the top of the thermocline was bounded by the 26°C isotherm along the Mississippi Delta Line (Figure III-4b). Beyond 100 nautical miles, the isotherm at the top of the thermocline was either 27°C or 28°C, but in all areas it was at least 1°C less than in August.

Above the thermocline, there was little indication of warm Mississippi River water along the offshore series of oceanographic stations on September 20-21. The only remnants of the extensive, pre-hurricane layer of brackish water lay east of the Delta.

Ten days after Hurricane Betsy had crossed the northern shelf of the Gulf of Mexico, the thermocline beneath and to the east of the path of the storm lay at depths between 40 and 50 meters (Figure III-6a). West of the path the top of the thermocline was between 20 and 50 meters. In all waters except those immediately beneath the path of the storm, the top of the thermocline was bounded by the 27°C isotherm. Beneath the path of the eye, 26°C continued to mark the top. Brackish water had returned to the surface layers mostly off the mouth of the Mississippi River.

Two days after the GUS III completed the line of stations off the Mississippi Delta, the ALAMINOS returned to the area (Figure III-6b). The differences in the temperature structures in the 2-to 3-day period were negligible. Those which appear to have been present, as depicted in Figures III-6a and 6b, can be disregarded because the GUS III was closer to the coast and occupied stations at shorter intervals than the R/V ALAMINOS.

The GUS III returned to the waters off the Delta about 1 month later (October 28, 1965, Figure III-6c). Although the earlier line of stations was not completed, it was clear that the effects of the hurricane were no longer present, and that changes from conditions in September were large.

Summary

It is clear that the waters over the northern shelf of the Gulf were profoundly modified by the hurricane. The typical surface waters near shore were removed and replaced by waters with oceanic characteristics. This change is best shown in the temperature profiles by the removal of warm, surface water. The influence of the hurricane extended to the greatest depths of the continental shelf (75 meters) so that water temperatures on the shelf floor were as much as 6°C warmer after the storm than before.

Upwelling in the upper 30 meters of the water column was evident at distances of about 60 nautical miles on either side of the eye of the hurricane. A 50-meter-thick layer of isothermal water lay on the surface at distances of about 100 nautical miles to either side of the path. Surface currents flowed strongly to the west in the area seaward from the Delta. Although modified to some degree, these features were still present 10 days after the storm had passed over the northern shelf.

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